Research Report

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Development of a Priority Ranking System for Bridge Rehabilitation or Replacement

by

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Commonwealth of Kentucky

and

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16. Abstract

The main objective of this study was to review a Bridge Priority Ranking System for Bridge Replacement developed by the Kentucky Transportation Cabinet Division of Maintenance. The system ranked bridges for improvement (rehabilitation or replacement) based on a benefit/cost ratio.

The system was used to rank a large data base consisting of 267 bridges. Analysis of the rankings revealed that the ranking system gave priority to bridges having low improvement costs. Many of those had low traffic volumes and subsequently, they had high costs of improvement per vehicle served.

The equation used to compute bridge deficiency points was revised. Several proposed alternate ranking systems were analyzed. Those systems and their analyses are discussed.

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COMMONWEALTH OF KENTUCKY
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FRANKFORT, KENTUCKY 40622

MILO D. BRYANT
SECRETARY
AND
COMMISSIONER OF HIGHWAYS

WALLACE G. WILKINSON
GOVERNOR

March 29, 1991

Mr. Paul E. Toussaint
Division Administrator
Federal Highway Administration
330 West Broadway
Frankfort, Kentucky 40601

SUBJECT: IMPLEMENTATION STATEMENT
Research Study KYHPR 88-120
Computerized Bridge Management

Dear Mr. Toussaint:

The Kentucky Transportation Cabinet prepared a priority ranking system for ranking bridge replacement projects. Under this study, this ranking system was analyzed. The need for a modified ranking system was deemed desirable. An alternate ranking system was prepared by Kentucky Transportation Center personnel in cooperation with KyTC personnel.

The alternate ranking system has been adapted to rank bridge projects based upon data from the computerized National Bridge Information file. KyTC personnel have used the system to rank 340 bridges for rehabilitation or replacement as part of the present 6-year plan. It will be employed to rank future bridge replacement programs.

The objectives of the study were met and Kentucky Transportation Cabinet has been furnished with a functional ranking system to prioritize bridge improvements.

Sincerely,

O. G. Newman, P.E.
State Highway Engineer

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EXECUTIVE SUMMARY

The primary objective of this study was to review the Bridge Priority Ranking System for Bridge Replacement currently used by the Kentucky Transportation Cabinet to rank deficient bridges. That system ranks bridges for improvement (rehabilitation or replacement) based on a benefit/cost ratio. Benefits are expressed by numerical values reflecting improved bridge service derived by the improvement action which eliminates the deficiencies. The cost is the total expenditure for rehabilitation or replacement. Bridges having higher benefit cost ratios would be scheduled for improvement action ahead of lower ranked (and presumably less beneficial) bridges.

As part of the analysis, the system was used to rank 267 bridges that were candidates for rehabilitation or replacement. Data used in the ranking process came from National Bridge Inventory files. Analysis of derived rankings indicated that the ranking system tended to prioritize bridges having low improvement costs. Many of those bridges served low traffic volumes. That resulted in high rankings for bridges having high costs of improvement for each vehicle served. Based upon that observation and several minor inconsistencies detected in the deficiency rating process, the decision was made to either revise the ranking system or develop a new one.

Several alternate ranking systems were devised and evaluated. Some of those ranked bridges for rehabilitation or replacement based upon different relationships between derived benefits and costs of improvements. Analyses of those systems are discussed in the body of this report. The formulae for determining bridge deficiencies were revised. New methods were proposed for measuring benefits gained by removing those deficiencies.

A new ranking system was developed during the study and that system was adopted by the Kentucky Transportation Cabinet officials. It provides a ranking based upon an annual net benefit (expressed as a monetary value). Annual net benefits are defined as the annual worth of total benefits obtained by improving a bridge less the cost of that improvement on an annual basis. The annual worth of total benefits is obtained by multiplying a numerical measure of annual benefits for improving a bridge by a unit cost for achieving those benefits. The unit cost is derived from a large bridge data base. The bridges are ranked in descending order from highest to lowest value of annual net benefits.

The revised system was used to rank 340 bridges selected for the 6-year replacement program. Inspection of that ranking revealed that the annual net benefit ranking system prioritizes bridges having high traffic volumes and high service deficiencies. The influence of cost of improvement upon the ranking process is subordinated to annual worth of total benefits. The ranking system provides Transportation Cabinet officials with a new method of ranking bridges for rehabilitation or replacement that will realize high benefits for the funds allocated for bridge improvement.

1.0 INTRODUCTION

Highway departments are seeking improved methods to determine bridge funding requirements and to better direct limited funds for structural improvements. Previously employed intuitive methods of managerial decision-making, based upon practical experience, are being replaced and complemented by bridge management systems. Bridge management systems consist of a series of algorithms or programs that analyze large data bases and assist managers in making bridge-related decisions.

A typical data base common to every highway department is the National Bridge Inventory (NBI) file. That file is an inventory of all structures having spans greater than 20 feet. It contains bridge data such as dimensions, bridge type, sufficiency rating, cost of improvements, condition rating, appraisal rating, operating rating and posted load limits, age, estimated remaining service life, and condition ratings of key elements. The file includes route information such as structure location, route name, functional and trucking classification, detour length, bridge/route continuity, lack of traffic safety because of functional deficiency, and average daily traffic (1).

The NBI file is a readily accessible source of data that may be used for bridge management purposes. The department managing the NBI file is usually in the best position to perform the bridge management function. Usually, personnel of that department are closely associated with the bridge inspection and maintenance process. They are familiar with the strengths and limitations of the rating process and may be in the best position to decide the usefulness of that information. Those personnel are knowledgeable of unique agency coding practices. They also know important information related to use of the data, such as sources of funds, statutes or categories governing the use of funds, resources available to implement actions, and applicable time frames for utilizing funds.

Other files may be used with the NBI file to compliment the bridge management decision-making process. Such files include the recently implemented Roadway Characteristics File maintained by the Division of Planning. Information from two or more files may be retrieved for structures and routes to enhance the decision-making process related to bridge/route compatibility.

For any bridge management system, it is highly desirable to have detailed data such as truck-volumes. Those data may be difficult to obtain. Comprehensive data may exist for one route, but not another. The lack of sufficient or complete information is a major obstacle in preparing a bridge management system.

1.1 Bridge Management Systems

A preliminary task in developing bridge management systems involves determining what computer-based information is required or desired. In a study of bridge management systems, six functions (modules) were identified as being essential to an operative bridge management system (2). Those are 1) a data base module; 2) a network maintenance, rehabilitation, and replacement (MR&R) selection module; 3) a maintenance module; 4) a historic data analysis module; 5) a project level interface module; and 6) a reporting module.

Normally, the data base module is a NBI file. File expansion may be desired to include bridge maintenance, rehabilitation, and replacement (MR&R) actions. Those data may be used to determine the distribution of remedial actions on a network basis. The data base module also serves as a historical record to be used in forecasting costs for future bridge work. The MR&R action data may be used with future condition ratings to assess the effectiveness of those actions. Incorporation of data inspection features into the data base may improve data reliability. A data base management program may be used with the NBI file to provide rudimentary reporting capabilities.

The network MR&R selection module may be as simple as a ranking program for prioritization of bridges for remedial or replacement action. Managers may specify the selection and prioritization process based upon their requirements. Some highway agencies do not consider repairs part of the action process and the selection of action is limited to major rehabilitation and replacement. A specific MR&R action submodule may be incorporated to achieve better selection between those actions based on benefit/cost analysis. Life-cycle costing and optimization submodules may be incorporated into the decision making process. They may be used as tools for selecting bridges, specifying maintenance actions, and predicting benefits related to alternatives. Those submodules are especially effective when restrictions exist due to a limited budget.

The maintenance module assigns and tracks routine maintenance programs for bridges excluded from the major MR&R program. Using a known funding level, the module prioritizes and ranks those maintenance activities.

The historical data analysis module records MR&R data and archives previous condition ratings. Those data allow projections of deterioration rates, forecasts of future MR&R budget requirements, and predictions of the effectiveness of work based upon previous MR&R actions.

The project level interfacing module may be used to send information between the NBI file and project level files. That will enable the rapid use of inventoried information for project purposes. It will also allow incorporation of project data such as construction costs, structural analyses, or planned route revisions.

1.2 Study Objectives

The primary objectives of this study were 1) to evaluate components and algorithms of existing bridge management systems used by other highway agencies with consideration for their adoption by the Kentucky Transportation Cabinet, 2) to review the Division of Maintenance Bridge Replacement Priority Ranking System (BRPRS) and provide recommendations for revisions, 3) to analyze existing and impending data bases maintained by the Kentucky Transportation Cabinet and determine the utility of that information and recommend changes to those systems that will enhance their compatibility and use in providing information for a bridge management system, and 4) to provide recommendations for establishing a future bridge needs information system (and possibly an optimized funding algorithm).

An effort was made to address all study objectives. The primary concern of Transportation Cabinet officials was in deriving a satisfactory BRPRS. Emphasis was placed upon that effort both in review and in production of an acceptable alternate. An acceptable BRPRS was produced in cooperation with the Divisions of Maintenance and Planning. Other study objectives received much less attention.

This was discussed at the February 1, 1989 Study Advisory Committee meeting (3). At that time, the Transportation Cabinet officials decided against extending this study for an additional year to meet all of the study objectives. The basis of that decision was the realization that implementation of a more comprehensive bridge management system incorporating all of its major functions would require a major commitment by Transportation Cabinet officials. Transportation Cabinet personnel were not prepared to undertake that endeavor and were of the opinion that further work in this area was unnecessary. This report will focus on the Kentucky Transportation Center (KTC) review of the Division of Maintenance BRPRS and the ranking system that was developed during this study.

1.3 Bridge Replacement Priority Ranking System

The Division of Maintenance original BRPRS uses deficiency points as a measure of functional shortfalls in geometric and structural conditions from target goals (4). Using that procedure, bridges having load postings, width or vertical clearance restrictions, or short remaining lives are assigned deficiency points. The degree of deficiency (that is, number of deficiency points) is based upon the type and number of shortfalls (in the assigned categories) and their severity. Bridges that have no load capacity deficiency (no posting), no width or vertical clearance deficiency, and significant remaining life are not assigned deficiency points.

In the Division of Maintenance BRPRS, deficiency points are summed for four different classifications (priorities) related to load capacity, deck width, vertical clearance, and estimated remaining life. A bridge condition rating factor is used to scale the summed deficiency points. The deficiency point formula is

$$DP = (LCP + WP + VP + LP) \times CRF \tag{1}$$

where

DP = total deficiency points (ranging from 0 to 130),
LCP = load capacity priority,
WP = width priority,
VP = vertical clearance priority,
LP = estimated remaining life priority, and
CRF = condition rating factor.

Load capacity has a maximum of 60 deficiency points. Load capacity deficiency points are totalled for four types of trucks: type 1 (two-axle, single unit), type 2 (three-axle, single unit), type 3 (four axle, single unit), and type 4 (semi trailer). The formula is

$$LCP(tot) = LCP(ty4) + LCP(ty3) + LCP(ty2) + LCP(ty1) \quad (2)$$

where

$$LCP(tyN) = WC \times IF(N) \times [(\text{acceptable capacity}(N) - \text{load rating}(N)] \times LRF_N/LRFT_N) \times KF \quad (3)$$

and

WC = LCP weighing factor = 0.6,
IF(N) = impact factor for a particular truck type and trucking classification route (Table 1),
accept. capacity(N) = legal load capacity (tons) at operating stress levels for a particular truck type (Table 2),
load rating (N) = actual load rating for a particular truck type (tons),
LRF_N = IF(N)/10,
$LRFT_N$ = acceptable capacity(N) - 3 tons* (*3 tons is the minimum permissible load limit),
KF = (.6KA + .4KD),
KA = $ADTO^{0.3}/11.26$,
KD = DL/20 x ADTO/3,200,
ADTO = average daily traffic over bridge,
DL = detour length (miles).

Width priority has a maximum of 15 deficiency points. The width priority formula is

$$WP = 15 \times [(5 - \text{deck geometry appraisal rating})/3]. \quad (4)$$

Vertical clearance priority has a maximum of 15 deficiency points. The vertical clearance priority formula is

$$VP = VPO + VPU \quad (5)$$

where

VPO = 7.5 x [(5 - overclearance appraisal rating) x (ADTO)/3,200],
VPU = 7.5 x [(5 - underclearance appraisal rating) x (ADTU)/3,200],
ADTU = average daily traffic under bridge.

The estimated remaining life has a maximum of 10 deficiency points. The estimated remaining life priority formula is

$$LP = 10 \times [1 - (RL - 3)/12] \quad (6)$$

where

RL = estimated remaining life (years).

The condition rating factor (CRF) depends upon superstructure type and condition rating. It is a scaling factor that ranges from 0.90 for concrete bridges having superstructure condition ratings greater than 5, to 1.3 for fracture-critical steel bridges having superstructure condition ratings less than 4 (Table 3).

Once the total deficiency points (DP) are computed for a structure, the priority factor (PF) ranking is determined by the formula

$$PF = (DP/CI) \times 100 \tag{7}$$

where

CI = cost of improvement (rehabilitation or replacement-in dollars).

Bridges are prioritized for rehabilitation or replacement by ranking them in descending order from the highest to lowest priority factor. The priority ranking factor is a benefit/cost ratio. The benefit is measured in terms of deficiency points removed and the cost is the project cost for bridge rehabilitation or replacement. Bridges having higher benefit/cost ratios (priority factors) are considered better candidates for those actions. Bridges to be improved (rehabilitated or replaced) are determined by successively selecting projects beginning with the highest ranked bridges until the sum of the CI values equals or approaches the limit of available funding.

Soon, after receiving the original formula from the Division of Maintenance, KTC personnel were furnished with a revised deficiency point equation

$$\begin{aligned} DP = {} & (LCP + WP + VP + LP) \times CRF \times \\ & (\text{Note \#1}) \times (\text{Note \#2}) \times KF \end{aligned} \tag{8}$$

where

Note #1 = school bus route factor (1.0 or 2.0)
Note #2 = closed/barricade factor (0.5, 1.0, or 2.0).

This replaced the original equation and was the basis for the initial KTC analyses. During those analyses, the school bus route factor was not employed because counties had not provided Division of Maintenance personnel with the information necessary to identify school bus routes.

Division of Maintenance officials' approach to bridge ranking for improvement actions was patterned after the North Carolina Department of Transportation system. That system was developed by North Carolina State University investigators (5). Several states have adopted that system, usually with minor modifications.

The Kentucky system varies from the North Carolina system in several respects. The North Carolina system is based upon several defined level of service goals. Deficiency points are calculated as departures from those goals. The Kentucky goals are based upon impact factors (for load capacity priority) and appraisal ratings. The Kentucky system incorporates a condition rating factor not used in the North Carolina system.

The Division of Maintenance condition rating factor is a special consideration for the effect of deterioration upon various types of structures. A reinforced concrete bridge would be more tolerant of significant deterioration than a fracture-critical steel bridge. The condition rating factor increases the number of deficiency points assigned to structures susceptible to failure at low condition ratings. The objective is to target those structures for more imminent replacement or rehabilitation.

The North Carolina System level of service goals are based upon four general functional classifications. The Kentucky system is based upon four trucking route classifications -- "AAA" for 80,000-lb load limits, "AA" for 62,000-lb load limits, "A" for 44,000-lb load limits. The "C" designation is applied to county roads. Those roads have 36,000-lb load limits. Those classifications vary somewhat with functional classifications except major roads such as interstate routes which all belong to the "AAA" trucking classification. The NBI file contains route trucking classification information for each bridge.

2.0 RANKING SYSTEM ANALYSES

The Division of Maintenance BRPRS employed numerical values for the impact factors, condition rating factors, and appraisal ratings used to calculate bridge deficiency points. Those values and ratings covered a range of economic and safety issues that could not reasonably be addressed in a short period and without extensive research. As a reasonable alternative, KTC personnel chose to focus the analyses of the ranking system on the output (ranking) provided by that system for a group of bridges from the NBI file. KTC personnel were of the opinion that if the empirical components of the BRPRS were practical, it would provide a consistent, logical ranking. The system would require revision when that did not occur.

2.1 Deficiency Point Equation Analyses

KTC personnel requested NBI files on a large bridge data set. Division of Maintenance officials furnished data for 267 bridges. District personnel had previously recommended those bridges as candidates for rehabilitation or replacement in the 6-year plan.

Division of Maintenance officials supplied the data set on magnetic tape along with the code listings for data extraction. The file for each bridge consisted of 1,200 columns of data used to describe 211 items. Useful data for BRPRS analysis included inventory route number, location description, bypass length, functional classification, average daily traffic (over/under), superstructure condition rating, estimated remaining life, operating rating, vertical and horizontal clearance appraisal ratings, total cost of improvement (replacement), superstructure type, structure closed/open/posted, load capacity ratings (postings), deficiency points (LCP, WP, VP, LP, and DP), and priority factor.

Data were stored on the mainframe computer at the University of Kentucky Computing Center. Data runs were made using a portable computer at KTC linked to the mainframe by a modem. A fortran program was prepared to extract data from the file. Software from **Statistical Analysis Software Inc.** (SAS) was available on the mainframe computer and was used for data manipulation and analyses.

The first computer output was made to provide a numbered list of bridges which was correlated with the respective project number, inventory number, and location description. The identification numbers were used to identify particular structures among several successive computer outputs.

The statistics of the 267-bridge data set were analyzed. Examination of the 267-bridge data set revealed that 30.3 percent of the bridges were "A" trucking classification, 5.2 percent were "AA" trucking classification, 15.4 percent were "AAA" trucking classification, and 49.1 percent were "C" trucking classification. The average KF value was 0.55. The average CRF and closed/barricade factor notes were both 1.0. The average ADTO for the data set was 1,103 vehicles. The average detour length was 21.9 miles. The average LCP, WP, VP, and LP priority deficiency points were 28.7, 13.2, 0.1, and 4.8, respectively. The average total deficiency point value DP was 19.4. The average cost of improvement was $501,000.

The first analysis concentrated on the benefit (deficiency point) portion of the ranking system. Data for the various input parameters related to calculation of total deficiency points (Equation 8) was inspected. The first observation was that major differences existed between bridges of the different trucking classifications. Those differences were most apparent in contrasting the average values of parameters for the "C" bridges with those of the "AAA" bridges. In most cases, averages of parameters for the "A" and "AA" bridges were between the extreme limits set by the "C" and "AAA" bridges.

Typical "C" bridges had high priority deficiency point totals (61.4 avg.) and low ADTOs (185 avg.) with corresponding low KF multipliers (0.24 avg.). Typical "AAA" bridges had low priority deficiency point totals (16.3 avg.) and high ADTOs (4,051 avg.) with corresponding high KF multipliers (1.59 avg.). The result in terms of total deficiency points was similar (17.1 avg. and 24.4 avg. respectively for the "C" and "AAA" bridges.

Inspection of the LCP, WP, VP, and LP priorities provided further insight related to total deficiency points. Many of the "C" bridges had high LCP priority deficiency point totals (40.6 avg.) compared to "AAA" bridges (1.4 avg.) many of which had no LCP priority deficiency points.

Due to low appraisal ratings, nearly all of the bridges in the data set had WP priority deficiency points. A large number of those bridges had the maximum allocation of 15 WP priority deficiency points (91 and 71 percent, respectively, for the "C" and "AAA" bridges).

VP priority deficiency points had a negligible affect on the ranking process. Only eight bridges had VP priority deficiency points. Only one of those was greater than 2.5

priority deficiency points.

The LP priority deficiency points were assigned to structures having significant, visible deterioration. As anticipated, "C" bridges had higher LP priority deficiency points (6.5 avg.) than "AAA" bridges (2.1 avg.). Nearly half of the "C" bridges had the maximum allocation of 10 LP priority deficiency points.

An overview of the data indicates that typical "C" bridges are in a deteriorating state. They are structurally deficient and functionally obsolete. They serve low traffic volumes. Conversely, the typical "AAA" bridges are reasonably well preserved. They are structurally acceptable, but functionally deficient. They serve high traffic volumes. As with comparison of the parameter data, the descriptions of typical "A" and "AA" bridges lie between those described for the "C" and "AAA" bridges.

The second computer output ordered the bridges by total deficiency points. The top 50 bridges ranked by total deficiency points in descending order from the highest to lowest. Those are listed in Table 4.

Most of the bridges having the highest total deficiency points had high ADTOs and detour lengths. Most of those bridges had high WP and LP priority deficiency points. LCP priority deficiency points were not essential for bridges with high total deficiency points. Twenty percent of the top 50 bridges had fewer than 5 LCP priority deficiency points. All of those were "AAA" bridges with WP and, in some cases, LP priority deficiency points. Those were in combination with high traffic volumes and detour lengths.

Beyond the 15 bridges having the highest total deficiency points, the difference in deficiency points between succeeding bridges decreased significantly. That indicated that the ranking procedure would be highly dependant upon construction or rehabilitation costs. Accurate cost estimates were essential.

The effect of the closed/barricade factor was considered significant since six of the top 50 bridges had barricade factors of 2.0. Only one other bridge in the data set had a closed/barricade factor of 2.0.

The condition rating factor did not have a significant impact upon the deficiency point totals. Twenty-four of the top 50 bridges had condition rating factors greater than 1.0. Twenty-three of the next ranked 50 bridges also had condition rating factors greater than 1.0.

High KF values are due to a combination of high ADTO and detour values. The combination of high ADTO and WP values should be reflected in high total deficiency points. WP deficiency points indicate that bridge components such as barriers, curbs, and superstructures are narrow in relation to the roadway and pose an accident hazard. The degree of risk is also related to the functional classification, speed limit, and traffic volumes. WP deficiency points should reflect those factors. However, there is no apparent relationship between WP deficiency points and detour length. Vehicles will rarely be detoured for width reasons. The detour length is primarily for LCP deficiency considerations.

A number of the top 50 bridges listed in Table 4 had combinations WP priority deficiency points and high KF multipliers where detour length contributed significantly to the KF value. The analysis indicated that it might be more desirable to rearrange the deficiency point equation into the original format (Equation 1). Detour length is only a factor for LCP deficiency points in that equation.

2.2 Priority Factor Analyses

The priority factors (PF) for the bridges were calculated according to Equation 7 and the bridges were ranked in descending order (Table 5). Inspection of the outputs revealed that CI values have greater impact upon the priority factor than total deficiency points. The average CI values for the "C" bridges was only $ 241,000 compared to an average CI value of $ 1,597,000 for the "AAA" bridges. As a result of the lower CI value, the average priority factor for the "C" bridges was higher than that of the "AAA" bridges. As with the deficiency point parameters, average CI values for "A" and "AA" bridges ($ 394,000 and $ 337,000 respectively) were between those of the "C" and "AAA" bridges.

The effect of cost of improvement on the rating process may be determined by comparing those costs for the top 20 bridges ranked by total deficiency points and by priority factors. The sum of CI values for the top 20 bridges ranked by total deficiency points was $ 56,240,000. The sum of the CI values for the top 20 bridges ranked by priority factors was $ 2,091,000. Ranking bridges solely by total deficiency points results in a higher per structure cost of improvement. More ADTOs are affected than for bridges ranked by priority factors.

If total deficiency points were used to rank the top 20 bridges, 91 percent of the cost would be allocated to rehabilitate or repair nine "AAA" bridges. The balance of funding would be in the proportions of 6.5, 1.2, and 1.1 percent, respectively, for "C", "AA", and "A" bridges. For bridges ranked by the priority factors, the costs of improvements are more widely distributed with 47.9, 30.8, 19.8, and 1.5 percent, respectively, assigned to "C" , "AA", "A", and "AAA" bridges.

The priority factor ranking favors bridges having low costs of improvement. For a given level of funding, it ranks more bridges for improvements than a ranking system based upon total deficiency points. As many of the bridges having low costs of improvements are small "C" and "A" bridges with low ADTOs, the bridges selected would have less impact on motorists. Table 5 reveals that bridges ranked by the priority factor have varying costs of improvements per ADTO. The eighth-ranked bridge by priority factor has a cost of improvement per ADTO 80 times greater than the ninth ranked bridge. Many bridges that have high priority factor rankings also have higher costs per ADTO than lower ranked bridges. That indicates that the benefits given by the total deficiency points in Equation 8 do not compensate sufficiently to offset the effect of costs of improvements in ranking bridges by Equation 7.

Based upon those analyses, KTC personnel recommended development of a new priority ranking system. They also recommended revision of the method to calculate ~~deficiency points (Equation 8).~~

3.0 REVISED DEFICIENCY POINT EQUATION

Concurrent with the development of alternate ranking systems, discussions were held concerning the deficiency point equation. KyTC personnel decided to revise the deficiency point equation to remove shortcomings that had been discovered during review.

It was determined that the VP and WP appraisal ratings used to calculate VP and WP priority deficiency points included traffic provisions. It was concluded that the KF multiplier should not be used to scale those values. The decision was made to revise the equation in its original form and to use the KF multiplier only for LCP priority deficiency points.

Early in the analysis of the deficiency point equation, the files for concrete bridges in the 267-bridge data set were reviewed to determine if they would provide insights about a family of similar structures. The review revealed that only 21 of the 82 bridges listed had over 20 total deficiency points. Only 16 of those bridges had over 25 LCP priority deficiency points. Forty nine of those bridges had estimated remaining lives of less than 15 years and were assigned LP deficiency points.

Inspectors provided the remaining life estimates. Review of the bridge data indicated that those estimates should be improved if they were to be used in the priority ranking formula. While many of those bridges had low riding surface ratings, only two had low deck or substructure condition ratings that warranted prompt remedial action. Many of the concrete bridges having estimated remaining lives less than 15 years will probably serve for many years beyond the inspectors' predictions.

At the time of that analysis, FHWA officials discontinued the requirement for information on estimated remaining bridge life on the revised NBI system. That may indicate that FHWA officials were not satisfied with the remaining life estimates provided by most highway agencies. Division of Maintenance personnel decided not to retain estimated remaining life data in the revised NBI file. As a result, the LP priority was removed from the deficiency point equation and the LCP priority deficiency point limit was increased to 70.

The closed/barricade factor in the revised deficiency point equation (8) was examined. The NBI file applied the factor only when a bridge was coded as closed. When a detour length was greater than 3 miles, the total deficiency points were increased by a factor of two. When a detour length was equal to 3 miles, the factor was one. However, when a detour length was less than 3 miles, the factor decreased to 0.5. In that situation, the total deficiency points of a bridge put out of service decreased by a factor of 2. After that issue was reviewed, the decision was made to remove the closed/barricade factor from the deficiency point equation.

The total number of priority deficiency points that could be assigned to a bridge was limited to 100. The maximum total deficiency points could be 130 due to the effect of the CRF. The decision was made to assign a closed bridge the maximum number of total deficiency points (130) that could be allotted for a structure. It was felt that regardless of type, a closed bridge should be assigned the highest number of total deficiency points.

KyTC personnel decided to provide an accommodation for school buses in the deficiency point equation. The weight of a standard loaded school bus was considered to be 13 tons. KyTC personnel also were of the opinion that smaller mini-buses could be employed with weights down to 8 tons. Bridges that could accommodate single-unit, two-axle trucks having a type 1 posting equal or greater than 13 tons would not be provided a multiplying factor. Bridges having type 1 postings less than 13 tons, but greater than 8 tons would have their LCP1 deficiency points increased by a factor of 1.25. Bridges having postings of less than 8 tons would have their LCP1 deficiency points increased by a factor of 1.5.

The effect of the LCP1 multiplier was to increase the LCP priority deficiency points to the maximum value (70) for single-load postings up to 6 tons for the "C", "A", and "AA" bridges. It did the same for "AAA" single-load postings up to 7 tons. The LCP priority deficiency points were increased on an average of 30, 25, 20, and 18 percent, respectively, for the "C", "A", "AA", and "AAA" bridges up to the 8-ton limit by the 1.5 multiplier. Between 9 to 13 tons, the LCP priority deficiency points were increased on an average 15, 13, 9, and 8 percent, respectively, for "C", "A", "AA", and "AAA" bridges.

A final revision to the deficiency point equation entailed revision of the KF equation. The original equation was based upon an ADT value of 3,200 vehicles as the standard for all road classifications. That biased the deficiency point equation (Equation 8) toward the "AA" and "AAA" bridges that had higher traffic volumes than "C" or "A" bridges. It was considered more desirable to compare bridge traffic volumes by relative differences within each particular trucking or functional classification.

Data on average traffic volumes for different trucking classifications could not be obtained. However, data that provided average traffic volumes for routes having various functional classifications were obtained (6). Functional classifications are based upon location: rural and urban, and on route type: principal arterial (interstate), principal arterial (other), minor arterial, major collector, minor collector, and local system.

A comparison of the ADTO for a route having the average traffic volume for the same functional classification would provide insight about its level of use and relative importance compared to similar routes. Bridges on routes of the same functional classification would be assigned deficiency points based upon their level of use relative to that functional classification.

The functional classification of the route of each bridge was contained in the NBI file and could readily be incorporated into the deficiency point equation. A program run was made using the 267-bridge data set. It used functional classification average traffic volumes in place of the 3,200-ADT value used in the original deficiency point equation.

That revision increased the average KF value for all bridge types from 0.550 to 0.835. The main effect was to increase the average KF values more for "C" and "A" bridges than for the "AA" and "AAA" bridges. The average KF values for the "C" and "A" bridges increased by 117 and 96 percent, respectively. The average KF values for the "AA" and "AAA" classifications increased by 8 and 10 percent, respectively. When that revision was made, KF was also changed to a multiplier for LCP priority deficiency points instead of all priority deficiency points as with Equation 8. As a result, the KF revision did not have a pronounced effect upon the total deficiency points.

The revised deficiency point formula used to analyze the subsequent ranking factors was

$$DP = (LCPTOT + WP + VP) \times CRF \tag{10}$$

where

$$LCPTOT = LCP(ty1) + LCP(ty2) + LCP(ty3) + LCP(ty4)$$

and

$$LCP(n) = WF \times IF \times [\text{Acceptable Capacity } (n) - \text{Actual Load Capacity}(n)] \times 1/LRFT_N \times MF \times KF \tag{11}$$

where

WF = LCP weighing factor = 0.7,
MF = Multiplying factor which is 1.0 for LCP2, LCP3, and LCP4. LCP1 MF = 1.0 for actual load capacity equal to or greater than 13 tons; LCP1 MF = 1.25 for actual load rating between 8 and 13 tons; and LCP1 MF = 1.5 for actual load rating less than 8 tons.

and

$$KF = .6KA + .4KD$$

where

$$KA = (ADTO/ADTB)^{0.3},$$

$$KD = (DL/20 \times ADTO/ADTB),$$

and

ADTB = average ADT for the particular route functional classification.

The changes had some basic effects upon the deficiency point equation. Those changes were reflected in the averages for the 267-bridge data set. Equation 10 provided fewer average priority deficiency points (30.25) than Equation 8 (47.02). However, due to changes with the KF multiplier, the average total deficiency points for the data set derived by Equation 10 was greater (33.84) than the value derived by Equation 8 (19.45). The revised deficiency point equation increased the total deficiency points for the "C" and "A" bridges by 97 and 144 percent, respectively. It decreased the total deficiency points for the "AA" and "AAA" bridges by 39 and 42 percent, respectively.

4.0 ALTERNATE RANKING SYSTEMS

A balanced ranking method that would provide more user benefits and a better distribution of bridges by trucking classification was sought. A system employed by PennDOT uses several indexes to determine ranking for rehabilitation or replacement (7). The indexes are composed of improvement costs, total deficiency points, ADTOs, and structure lane length.

4.1 Ranking Factor Index System

KTC investigators devised a system incorporating seven ranking factor indexes to measure bridge deficiency (8). The seven ranking factor indexes were 1) RDP - ranking by total deficiency points as calculated by Equation 8, 2) RPF - ranking by priority factor, 3) RCPADT - ranking by cost of improvements per ADTO, 4) RCPAIL - ranking based upon cost of improvements per ADT per improvement length, 5) RDPCPAIL - ranking based upon deficiency points removed per cost of improvements per ADTO per improvement length, 6) RSR - ranking based on federal sufficiency rating, and 7) RDPCA - ranking based upon deficiency points per cost of improvements per ADTO. Each bridge in a data set was to be assigned a number for each ranking factor index based upon the order of ranking within each factor. The bridges were ranked in ascending order from the lowest numerical ranking of each index to the highest. The overall ranking factor, RF, was determined by summing the indexes as given by the equation

$$RF = RDP + RPF + RCPADT + RCPAIL + RDPCPAIL + RSR + RDPCA \quad (9).$$

The ranking factor indexes could be modified by assigning weighing factors to each index to produce the desired emphasis for ranking. Ranking was performed in ascending order from the lowest to the highest numerical RF value.

A computer output was prepared using this system. Three of the top four ranked bridges in this system were similarly ranked by total deficiency points. The top twenty bridges ranked by the new system had a compositions of six "A", three "AA", three "AAA", and eight "C" bridges. The top 20 bridges ranked by the priority factor included only one "AAA" bridge. The percentage of money spent on the different bridge types was 20, 9, 34, and 37 percent for the "A", "AA", "AAA", and "C" bridges respectively. In contrast, nearly half of the total cost of improvements for the top 20 ranked bridges based on the priority factor (Equation 7) were ranking targeted to improve "C" bridges.

KyTC personnel reviewed the proposed ranking method but judged that it did not meet their needs.

4.2 Net Benefit Ranking System

Instead of the adopting the KTC proposed ranking system, KyTC personnel suggested investigation of a ranking system based upon net benefits. The equation investigated was

$$NBRF = [(DP \times ADTO/\Sigma\, DP \times ADTO) - (CI/\Sigma\, CI)] \times 100 \qquad (12)$$

where

NBRF = net benefit ranking factor,
Σ DP x ADTO = sum of the products of deficiency points times ADTs over a bridge for all bridges in a data set,
Σ CI = sum of the costs for improvements of all bridges in a data set.

To employ that ranking equation, a compilation would be made of all bridges in a data set (that is, the bridges recommended for improvement by the districts) along with their DP and CI values and the products of DP x ADTO. The DP x ADTO and CI values would be summed for the entire data set. Then, each bridge would receive the resulting ranking factor determined by Equation 12 to prioritize it for improvement. The ranking factor depends upon the amount of total benefits for an improvement (DP x ADTO normalized for the data set by dividing the Σ DP x ADTO) less the cost of improvement (CI normalized for the data set by dividing Σ CI). A higher net benefit would provide a higher ranking for rehabilitation or replacement.

The 267-bridge data set was ranked by the net benefit ranking equation. The top 50 ranked bridges are listed in Table 6. That ranking system favored bridges having high ADTOs. Eighteen of the top 20 ranked bridges had ADTOs exceeding 1,000 vehicles. Eleven of those bridges had more than 30 total deficiency points. The net benefit ranking system rated "AAA" bridges higher than "C" bridges.

Several limitations were discerned for the net benefit ranking equation. For the 267-bridge data set, Σ CI = $ 133,798,000 and Σ (DP x ADTO) = 8,078,932. The Σ CI is about 16.5 times greater than Σ (DP x ADT). As a result of that difference, the numeric values of DP x ADT in Equation 10 have a greater impact on the net benefit ranking than those of CI. This is shown by comparing bridge nos. 11 and 14 in Table 6. Those bridges have DP x ADTO values of 77,044 and 72,946, respectively. The costs of improvements for those bridges were $ 65,000 and $ 30,000, respectively. While the difference in DP x ADTO was only 4,098, the bridge no. 11 costs almost twice as much to improve as the lower ranked bridge no. 14.

Inspection of the rankings revealed that by comparing groups of bridges (bundling), more net benefits could be provided for a given funding level than by choosing individual bridges based upon the ranking factor. For example, bridge no. 16 in Table 6 had a higher net-benefit ranking factor than either bridges nos. 17 and 18. By improving those two bridges in combination, a greater net benefit could be achieved than by improving bridge no. 16. Also, the net benefits could be achieved at a lower cost. Inspection of the data set revealed other combinations of bridges that provided similar benefits.

A third problem was encountered when using the net benefit ranking system on the 267-bridge data set. The net benefit value became negative at the bridge ranked no. 82. This occurred when the normalized DP x ADTO component became small in relation to the costs of improvements. The apparent implication of a negative net benefit is that it is better to improve a bridge having few or no total deficiency points that may be repaired cheaply rather than to improve a bridge having high total deficiency points and a high cost of improvement. For example, the bridge ranked no. 256 in the data set had no deficiency points, but ranked higher than 11 other bridges having deficiency points.

4.3 User Oriented Ranking Systems

KTC investigators sought to determine whether other cost-benefit ranking criteria could be considered as alternatives to the net benefit ranking equation. Seven ranking criteria were used including the priority factor (Equation 7) and the net-benefit ranking factor (Equation 12). The other ranking factor equations investigated were

$$RF = (DP \times ADTO/CI) \qquad (13)$$

$$RF = (DP^2 \times ADTO/CI) \qquad (14)$$

$$RF = (DP^2/CI) \qquad (15)$$

$$RF = (DP \times ADTO^{0.5}/CI) \qquad (16)$$

$$RF = (DP^2 \times ADTO^{0.5}/CI) \qquad (17).$$

Equation 7 is a benefit/cost ratio that is not user oriented. The net benefit ranking factor (Equation 12) is basically the normalized total benefit less the normalized cost of improvement. Equation 13 is a benefit/cost ratio that is user oriented since ADTOs are included in computing benefits. Equations 14-17 are modifications to those basic equations which place emphasis on DP and ADTO nonlinearly with respect to RF. Those relationships were examined to determine their effect upon the ranking process.

The rankings were computed for the different methods using the revised deficiency point equation (Equation 10) on the 267-bridge data set. The ranking systems compared were based upon the top 10 bridges ranked by each method (Table 7).

As expected, the 10 top bridges ranked by Equation 7 would remove the most deficiency points of any of the ranking equations. It also would serve the least ADTOs and would have the second highest unit cost per total benefit (CI/DP x ADTO).

Improvement of the ten bridges by Equation 12 would yield the greatest total benefit (CI/ADTO). That benefit would be achieved at the highest total costs of improvements for 10 bridges and at the highest unit cost per total benefit. The ten top bridges ranked by Equation 12 served the most vehicles (ADTOs). Improvement of those bridges would remove the fewest deficiency points. The ten top ranked bridges by Equation 13 would have the lowest unit cost per total benefits of all of the ranking equations.

The bridges ranked by Equations 14-17 would have lower costs of improvements than the bridges ranked by Equation 7. They also would have lower costs of improvements than the bridges ranked by Equations 12 or 13. The ten top ranked bridges by those equations served fewer ADTOs than either Equations 12 or 13.

That analysis revealed ranking equation variables may be modified to yield the desired emphasis based upon cost/benefit indicators such as CI/ADTO, CI/ ADTO x DP, or CI/DP. Those indicators can also serve as ranking factors. Such modifications allow the selection of a ranking equation that produces the optimum or desired result. For example, Equation 13 might be used when the lowest cost per unit of total benefit was desired.

4.4 Zero-One Programming (Optimization)

KTC personnel investigated bridge selection/ranking by optimization using zero-one programming. That method is used to maximize benefits of the selection process. Typically, that type of computer programming solves capital budgeting problems. Those problems involve selection of a single or group of projects from a larger group of mutually exclusive projects. The purpose is to select projects that will provide the maximum net benefit for a fixed budget (9). For a few projects, the selection process may be performed by bundling (grouping). A mathematical programming approach must be used for large numbers of projects.

Mathematically, the process may be stated as

$$\text{maximize } Z = \sum_{i=1}^{n} (NB)_i x_i \tag{18}$$

subject to the constraint

$$\sum_{i=1}^{n} K_i x_i \leq B$$

and

$$x_i = 0 \text{ or } 1 \text{ for all } i$$

where

Z = cumulative net benefit for the selected projects,
NB_i = net benefit for Project i,
K_i = cost of improvement,
n = number of projects,
x_i = decision variable for Project i, and
B = budget restriction.

A zero-one computer program was obtained, tested for function, and adopted for analyzing the bridge improvement selection process (10). It was used to analyze a reduced data set due to the large amount of computing time the program required. The top 75 bridges of the 267-bridge data set, as determined by the net-benefit ranking equation, were selected for zero-one analysis.

The net benefit was determined by selecting a net benefit formula

$$NB_i = (U \times DP_i \times ADTO_i) - CI_i \qquad (19)$$

where

U = average unit cost/benefit ratio for the data set,

$= \Sigma\, CI / \Sigma\, DP \times ADTO.$

The first computer output had a negative net benefit after the nineteenth bridge. That was due to the limited size of the data set. The data for those bridges provided a low value for U and large net benefits for the highest ranked bridges.

For a small budget constraint of 1.5 million dollars, the program selected seven bridges. One rejected bridge had a higher net benefit than either of the two bridges that were selected. However, those two bridges taken in combination provided proportionally more benefits for their relative costs and also fit in the budget constraint of the zero-one program.

The zero-one algorithm selected various combinations of bridges when the budget constraint was increased in successive runs to 2 and 3 million dollars. It selected several bridges that were rejected for the 1.5-million dollar limit. It also rejected one bridge that was selected using that lower budget constraint.

The program would not process the data set when the budget constraint required the program to select projects having negative net benefits. To overcome that problem, the value of U was changed to

$$U = U_{max} = (CI/DP \times ADTO)_{max} \text{ for the data set}$$

That provided positive net benefits for all bridges in the data set.

The data set was reprocessed using the new unit cost/benefit ratio and budget constraints of 8 and 25 million dollars. The program required 50,500 iterations to derive a final output for the 8-million dollar budget and 690 iterations for the 25-million dollar budget. For the 8-million dollar budget, 36 bridges were selected including one ranked as low as no. 47 in net benefits. For the 25-million dollar budget, 47 bridges were selected including one ranked as low as no. 63 in net benefits. In both cases, several higher ranked bridges were rejected by the algorithm to maximize total net benefits.

Additional outputs were generated varying U slightly by a factor of 0.8 and 1.2 and comparing bridge selections with budget constraints of 8 and 25 million dollars. Varying the value of U (and the net benefits) caused slight changes in the particular bridges and the number of bridges selected. In each case, the slight differences in U did not affect most of the bridges selected. The changes in bridge selection involved a few bridges having low net benefits. That indicated the selection of bridges by zero-one programming was relatively insensitive to changes in U.

Other data outputs were generated to determine the gain in net benefits that might be achieved using the zero-one program compared to the selection process using a ranking procedure. The effect of budget size was analyzed by performing computer runs with budget constraints of 5, 8, 15, 20, and 25 million dollars. The net benefit was calculated using $U = U_{max}$. Using the zero-one programming, the net benefits for each funding level were higher than those obtained by net benefit ranking (Equation 19). Those increases were 8.0, 5.5, 10.9, 3.6, and 0.7 percent for those respective budget constraints. Those outputs demonstrated that when the budget included most of the bridges in a data set, zero-one programming would not be useful. Zero-one programming would provide a significant gain in net benefits when a budget rejected about half of the projects in the data set.

Zero-one programming was not adopted for several reasons. The project selection process is performed by KyTC personnel from a list of bridges furnished by the districts. Only a ranking process is needed to prioritize those bridges for the 6-year plan. That would not utilize zero-one programming to its best advantage since projects in the data set of selected bridges could not be rejected. It would be difficult to convince local officials of the correctness of the zero-one program selection process which selected lower ranked projects over a higher ranked ones.

5.0 ANNUAL NET BENEFIT RANKING SYSTEM

KyTC personnel favored ranking projects by a method similar to Equation 19. They proposed a new ranking system based on annual net benefits. In that proposed ranking system, total annual benefits were defined as DP x ADTO x 365 days/year in that proposed system. A unit cost, U, of achieving those benefits would be derived for the data set of bridges that were to be ranked. The total value or worth of those benefits is defined as the product of the total annual benefits times the unit cost. The annual cost of a bridge is determined and the worth of net benefits is obtained by subtracting the amortized annual cost from the annual worth of total benefits.

The net benefits are determined on an annual basis since it is difficult to predict the future worth of benefits, especially over a long-time interval. The annual cost of the bridge is derived by assuming that the bridge will not need further work for a 20-year period after the improvement action. Based upon that assumption, the annual cost of the bridge is based on the cost of improvement, CI, amortized over 20 years at 10 percent interest.

The projects would be ranked in descending order from the highest to the lowest net benefits. KyTC personnel favored this ranking system because the ranking is uncomplicated and the ranking term is expressed as a monetary amount. It could easily be understood by persons lacking technical backgrounds. The unit cost of achieving those benefits, U, could be considered as a measure of the unit price Transportation Cabinet officials were willing to pay for bridge improvement based upon motorists' use of those facilities.

That general approach to ranking was satisfactory. A new method was sought to determine benefits. It was obvious that the various deficiency point priorities could not be grouped together to determine benefits. LCP and VP deficiency points are related to truck ADTOs and detour length. WP deficiency points are related to all vehicles using a bridge. Separate benefit calculations were required as those priorities are related to different variables.

Truck ADTO values were required for each route to calculate the benefits for removing LCP + VP total deficiency points. An appropriate truck data file is prepared annually by KTC staff. That includes a summary of Division of Planning loadometer and vehicle classification data used to provide EAL estimates. The file divides the state into four regions (by districts) and provides estimates of percent trucks for functional route classifications in each region. That information could be coded for a software program and could be used to estimate truck ADTOs. The estimate would be based upon total ADTOs for a bridge and the truck percentage from the functional classification data for the specific route. Detour lengths required to calculate those benefits are provided in the NBI file.

Total benefits for the LCP + VP and WP priorities were then calculated. For the LCP + VP equation

$$\begin{aligned} BLCPVP = {} & ATDO \times PT/100 \times DL \times CRF \times \\ & 365 \times (LCP+VP) \end{aligned} \tag{20}$$

where

BLCPVP = benefits for annual truck-detour mile, LCP + WP total deficiency points removed,
PT = percent trucks from Division of Planning data compiled by KTC personnel based upon route

functional classification
and other data,
(LCP + VP) = sum of the load capacity and vertical
priority deficiency points.

For the WP equation

$$BWP = ADTO \times CRF \times WP \times 365 \tag{21}$$

where

BWP = benefits for annual vehicle-WP total deficiency points removed,
WP = width priority deficiency points.

Unit costs were required for the two categories of deficiency points (LCP + VP and WP). The simplest method to determine bridge improvement costs for the two categories was to determine the relative percentages of LCP + VP and WP deficiency points for the data set and use those percentages to divide the cost of improvement for a bridge into two components. Those LCP + VP and WP assigned costs of improvement and the LCP + VP and WP benefits could be used to derive two cost/benefit ratios for each bridge. LCP + VP and WP unit costs could be obtained from the cost/benefit ratios of the data. For each bridge, annual worth of benefits achieved by LCP + VP and WP deficiency point removal could be determined. Those would be obtained by multiplying the annual benefits in those categories by the respective unit costs. The annual worth of total benefits for a bridge improvement would be the sum of the values of the LCP +VP and WP annual worths of benefits.

Division of Maintenance personnel prepared a new data set for 340 bridges. Those bridges were scheduled for improvement actions in the next 6-year plan. That was to be the first set of bridges ranked by the BRPRS program.. Some of the bridges in that data set were also in the 267-bridge data set that KTC staff used to analyze the previous ranking equations.

A comparative review revealed the 340-bridge data set had an average ADTO of 1,720 vehicles compared to 1,155 for the 267-bridge data set. The average of total deficiency points for new set of bridges was slightly lower than values of the original set, 46.1 and 51.2, respectively. The average cost of improvement was higher, $ 670,500 compared to $ 501,100 for the original data set.

The percentage breakdown of LCP + VP and WP priority deficiency points was similar, 70.5 percent and 29.5 percent, respectively, for the new data set and 73.2 and 26.8 percent, respectively, for the old data set. The decision was made to use 70 and 30 percent, respectively, to assign costs for the LCP + VP and WP benefits.

The annual cost of improvements is determined for each category of each bridge by the equations

$$TBU1 = AACC \times 0.70 \times 100 \text{ cents/dollar} \tag{22}$$

$$= \text{LCP} + \text{VP deficiency point related annual cost of improvement (cents /year)},$$

and

$$TBU2 = AACC \times 0.30 \times 100 \text{ cents/dollar} \quad (23)$$

$$= \text{WP deficiency point related annual cost of improvement (cents/year)},$$

where

$$AACC = CI \times 0.11746$$

$$= \text{annual amortized construction cost calculated over a 20-year period at a 10 \% interest rate (dollars)}.$$

The cost/benefit ratios were determined for each category of each bridge by the equations

$$R1 = TBU1/BLCPVP \quad (24)$$

$$= \text{LCP} + \text{VP cost/benefit ratio},$$

and

$$R2 = TBU2/BWP \quad (25)$$

$$= \text{WP cost/benefit ratio}.$$

The ratios for each bridge were ranked in ascending order from lowest to highest. Sensitivity analyses were performed by plotting the cumulative frequency of each data point (bridge) against the respective R1 and R2 ratios (Figures 1 and 2). The inflection points in the plots were taken as the unit values for those data sets. The inflection points represent the portion of the bridge data set beyond which much larger incremental increases in unit costs will be necessary to improve additional bridges.

The annual unit cost of benefits for LCP + VP deficiency point removal, U1, was determined to be 40 cents per truck-detour mile-deficiency point. The annual unit cost of benefits for WP deficiency point removal, U2, was determined to be 6 cents per vehicle-deficiency point.

Those costs are specific to the data set being ranked. When a different set of bridges is ranked, new unit costs must be determined.

The worth of benefits for LCP+VP deficiency point removal is determined by the equation

$$CBLCPVP = U1 \times BLCPVP/100 \quad (26)$$

$$= \text{annual worth of benefits for removal of}$$

LCP+VP deficiency points (dollars),

where

U1 = annual unit cost of benefits for LCP+VP deficiency point removal (cents per truck-mile-deficiency point removed).

The worth of benefits for WP deficiency point removal is determined by the equation

$$CBWP = U2 \times BWP/100 \qquad (27)$$

= annual worth of benefits for removal of WP deficiency points (dollars),

U2 = annual unit cost of benefits for WP deficiency point removal (cents per vehicle-deficiency point removed).

The annual worth of total benefits for each bridge is determined by the equation

$$TB = (CBLCPVP + CBWP) \qquad (28)$$

= annual total worth of benefits for deficiency point removal (in dollars).

The annual net benefits for each bridge is

$$NB = TB - AACC \qquad (29)$$

= annual net benefits for deficiency point removal (in dollars).

The bridges are ranked for replacement or rehabilitation based upon the net benefits in descending order (highest to lowest).

The annual net benefit ranking for the top 50 bridges of the 340-bridge data set is shown in Table 8. Several bridges in the original 267-bridge data set were also included in the final 340 bridges selected for the 6-year rehabilitation or replacement plan. Six such bridges in the top 20 bridges ranked by Equation 8 were also ranked in the top 20 bridges by the Equation 29.

Inspection of that ranking revealed that it favors bridges having high ADTOs. Forty of those bridges had ADTOs exceeding 1,000 vehicles. The equation will provide a suitable ranking for low ADTO bridges when the deficiency points and detour lengths are sufficiently high. Nine of the top 50 ranked bridges had ADTOs less than 500 vehicles. The equation does not over emphasize the effect of trucks. Thirty of those bridges were on routes that had less than 5 percent truck traffic. Many of the top 50 ranked bridges had significant LCP priority deficiency points. Only 13 had less than 10 LCP deficiency points. A majority of those were "AA" or "AAA" bridges.

The system did not over emphasize inexpensive bridges having low ADTOs. Only five bridges included in the top 50 projects had ADTOs less than 500 vehicles and CIs less than $ 250,000. In most cases, the dollar amounts for the annual worth of total benefits for bridge improvements greatly exceeded the annual amortized cost of those improvements. As a result, the system provided high rankings for some expensive bridges all having ADTOs exceeding 500 vehicles. Six of the top 50 projects had CIs exceeding one million dollars.

After reviewing the output from this system for the 340-bridge data set, KyTC personnel determined that it should be adopted for use. If a simple cost/benefit ratio ranking system had been adopted, it is likely that many of those expensive projects would not have been highly ranked.

KTC personnel prepared and furnished KyTC with SAS-based software that could be loaded onto a mainframe computer from a PC. The software will: 1) acquire bridge data from the NBI file (as it was formatted in June 1989), 2) calculate deficiency points based upon the revised deficiency point equation, 3) calculate annual net benefits for each bridge based upon predetermined unit costs of deficiency point elimination (for LCP + VP and WP priorities respectively) and on estimated construction costs, 4) the program will rank the bridges for rehabilitation or replacement based upon annual net benefits in descending order (highest to lowest), and 5) the program will provide two printouts of bridge data including bridge identification (project number and location description), deficiency points, net benefits and ranking for bridge rehabilitation or replacement.

6.0 CONCLUSIONS

The annual net benefit ranking system developed during this study provides a balanced ranking of projects that meets the needs and intent of the Kentucky Transportation Cabinet. The system will provide a reasonable selection of projects. It does not appear to over emphasize any particular parameter(s) such as cost of improvement, deficiency points, or ADTO.

The desirable features of this approach to ranking are 1) it provides a monetary measure of the Kentucky Transportation Cabinet officials' willingness to fund bridge construction projects based upon use of those facilities, and 2) it ranks bridge improvements on a monetary basis. Those attributes are beneficial even though the dollar amount of the annual net benefits has been only established by definition only and not verified by economic analysis.

Most engineering decisions related to bridge management are monetary based. It is desireable to employ monetary values as early and widely as possible in the bridge management evaluation and decision-making processes. Since the new ranking system quantifies benefits in monetary terms, it is a notable advancement toward that goal.

Ideally, the annual net benefit dollar amounts should be reviewed. If economically proven dollar amounts can be assigned to benefits, the Transportation Cabinet will gain a useful method not only for justifying bridge improvements, but also for making other economic projections.

Ranking equation input data such as truck percentages and average traffic volumes for various functional classifications should be updated periodically. Consideration should be given to regularly review the equation and to improve the ranking system. One area for potential improvement is the determination of WP deficiency points based upon the width appraisal rating. That rating is high for most bridges considered for improvement. It consistently allots the maximum WP deficiency points. That inhibits the influence of the WP priority as a scaling factor for ranking bridges. Perhaps, a revised WP deficiency point algorithm can be derived based on review of traffic studies.

7.0 RECOMMENDATIONS

Recommendations are:

1. An economic review should be considered to assess the dollar amounts provided by the annual net benefit ranking system. Economic analysis should be performed to determine the actual economic value provided by deficiency point removal. If accurate monetary values can be derived, the net annual value of benefit ranking system could be revised to reflect those amounts. The economic review could be based on historic records of bridge/route projects and economic data furnished by bridges served by those routes.

2. A procedure should be established to update the data inputs for the ranking system on a regular basis. KyTC personnel could meet periodically to review the system and revise it when necessary.

3. Consideration should be given to develop a criterion for district-level selection of candidate bridges for rehabilitation or replacement.

4. Standard methods should be developed to provide accurate cost of improvement data for all bridges in the NBI inventory. That would enable preparation of a computer program to review the NBI file for candidate bridges. A list of candidate bridges could be furnished the districts from which they may make recommendations for improvement.

5. Consideration should be given to development of a system to track structural condition, to forecast deterioration, and to determine maintenance needs for the entire NBI inventory.

6. Accurate truck, ADTO, and cost of improvement data are needed to assess the total benefits for any proposed bridge work. During every fiscal year, a review of those data should be performed on a small percentage of the bridges being rehabilitated or replaced. That work should include traffic counts and monitoring of construction costs. The data should be compared to NBI file data to determine if accurate data are being provided for the annual net benefit ranking process.

7. Consideration should be given to establishing level-of-service goals for the bridge inventory. Those goals could compliment the present ranking system and would be a basis for future funding requests. The goals would be defined for 'acceptable' and 'desirable' categories of bridges similar to the North Carolina BRPRS. Structures that did not meet those goals could be targeted for eventual improvement.

8. Consideration should be given to reviewing bridges on a route-specific basis. Bridges that provided deficient service in relation to the others on a route could be selected for eventual improvement. Identification of those structures would also serve as a basis for future funding requests.

REFERENCES

1. Saito, M. and Sinha, K. C., "Review of Current Practices of Bridge Management at the State Level," **Transportation Research Record 1113**, Transportation Research Board, Washington, D.C., 1987, pp. 1-8.

2. Hudson, S. W., Carmichael, R. F. II, Moser, L.O., Hudson, W. R., and Wilkes,. W.J., **Bridge Management Systems**, National Cooperative Highway Research Program Report 300, Transportation Research Board, Washington D.C., December 1987, pp. 9-12.

3. Hopwood, T., Kentucky Transportation Center, letter to Duncan, A.W., Minutes of KYHPR 88-120 "Computerized Bridge Management" February 6, 1989.

4. Sutherland, R. K., Branch Manager, Division of Maintenance, Memorandum to Romine, A. R., Smith, D., Kelly, G., and Layman, T. on the Kentucky Bridge Replacement Priority Ranking System, Kentucky Transportation Cabinet, July 21, 1987.

5. Johnson, D. W., and Zia, P., **A Level of Service System for Bridge Evaluation**, Center for Transportation Engineering Studies, North Carolina State University, Raleigh, NC, August 1983.

6. Pigman, J.C., and Deacon, J.A., **Allocation of Highway Costs and Revenues,** University of Kentucky Transportation Research Program, Report No. UKTRP-88-8, March 1988.

7. **The Pennsylvania Bridge Management System, Executive Summary, First Year**, Bureau of Bridge and Roadway Technology, Pennsylvania Department of Transportation, Harrisburg, PA, April 1986.

8. Hopwood, T., Letter to R. Sutherland on an alternate ranking criteria for bridge rehabilitation and replacement, September 16, 1988.

9. Stevens, G.T.,Jr., **The Economic Analysis of Capital Investments for Managers and Engineers,** Reston Publishing Co., Reston, Virginia, pp 178-192.

10. Keuster, J.L., and Mize, J.H., **Optimization Techniques with Fortran**, McGraw-Hill, New York, New York, 1973, pp. 91-104.22

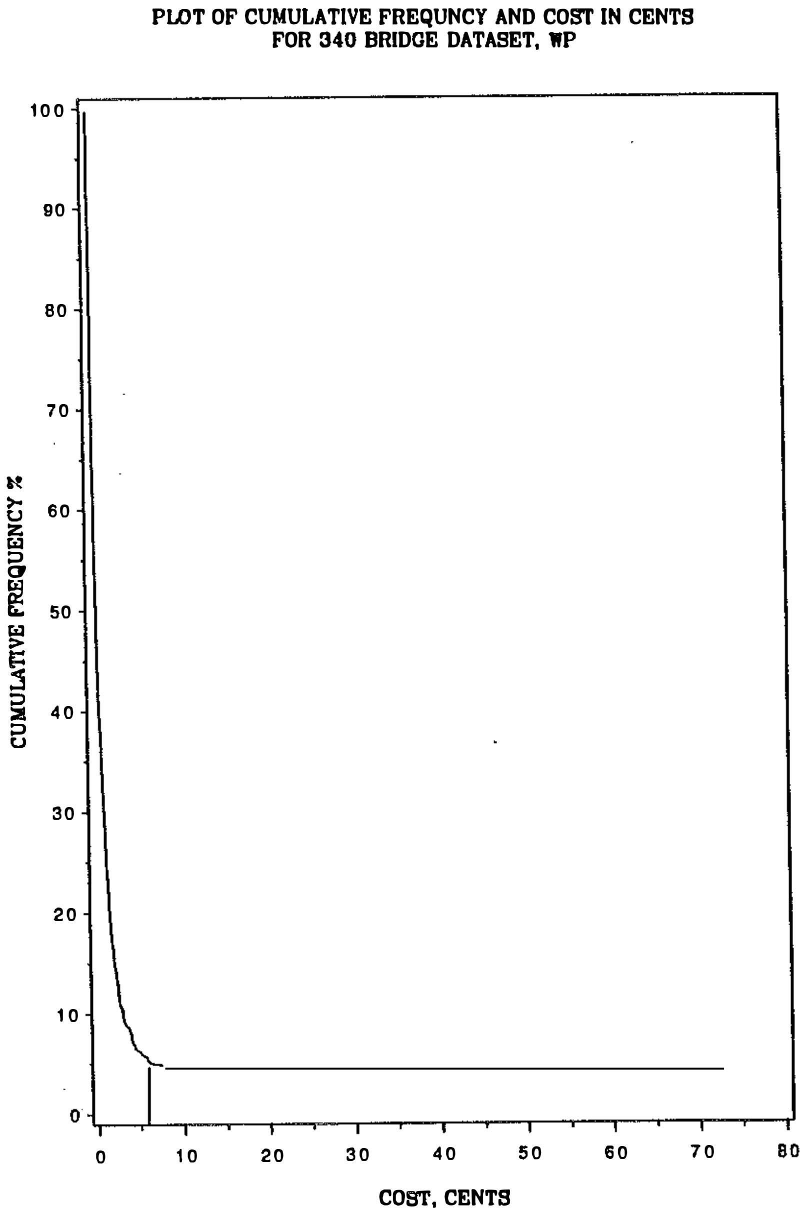

Figure 1. Plot of Cumulative Frequency and Cost in Cents for 340 Bridge Data Set, WP

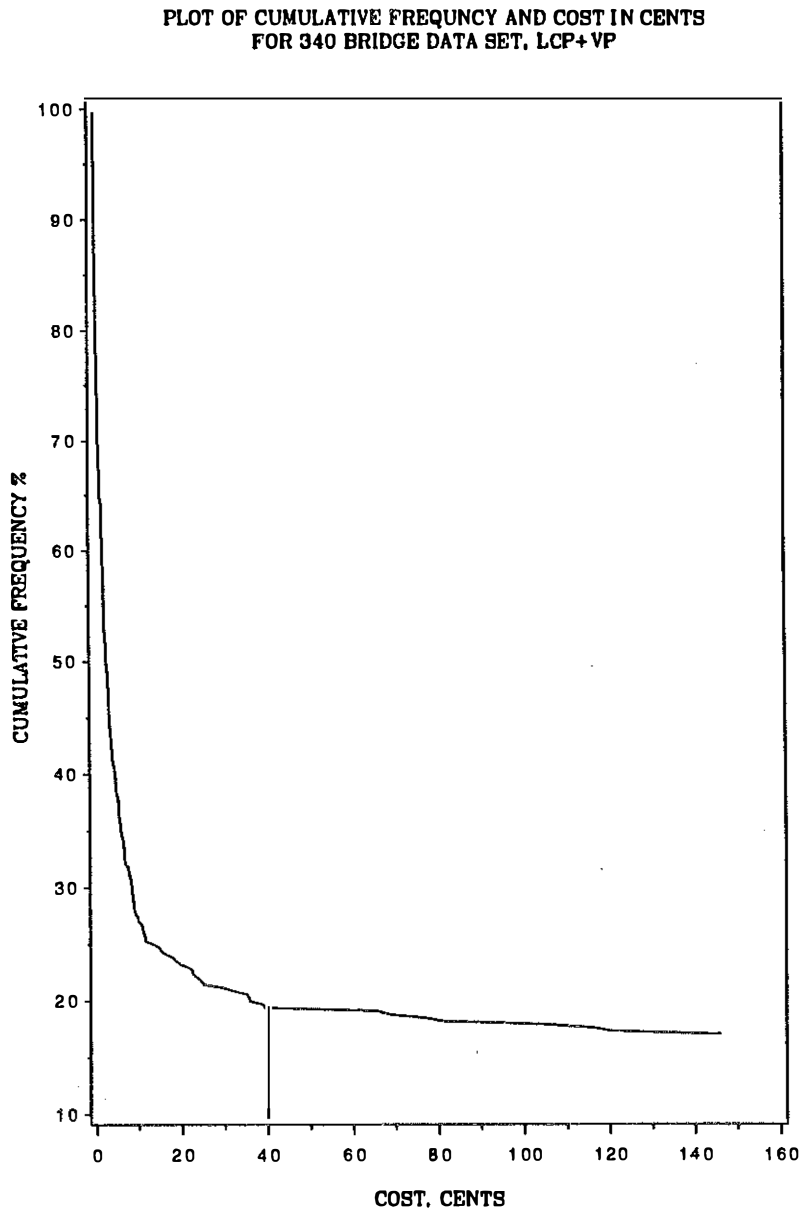

Figure 2. Plot of Cumulative Frequency and Cost in Cents for 340 Bridge Data Set, LCP + VP

TABLE 3. Condition Rating Factor Based on Superstructure Type and Condition Rating

Cond. Rat.	104,204 102,202 502,602	101,201 702,710	403	309,409 310,410	302,402 Others
	Structure Type				
9	0.90	1.10	1.00	1.0	1.0
8	0.90	1.10	1.00	1.0	1.0
7	0.90	1.10	1.00	1.0	1.0
6	0.90	1.10	1.00	1.0	1.0
5	0.95	1.15	1.00	1.0	1.0
4	1.00	1.20	1.15	1.0	1.1
3	1.10	1.20	1.30	1.2	1.1
2	1.20	1.20	1.30	1.20	1.2
1	1.20	1.20	1.30	1.20	1.2
0	1.20	1.20	1.30	1.20	1.2

Note. Structure Type Code

Ist Digit

1 Concrete
2 Concrete continuous
3 Steel
4 Steel continuous
5 Prestress concrete
6 Prestress concrete continuous
7 Timber
8 Masonry
9 Aluminum, W.I. or C.I.
0 Other

2nd and 3rd Digits

01 Slab
02 String./Multi-beam or girder
03 Girder and Floorbeam Syst.
04 Tee Beam
05 Box Beam or Gird.- Mult.
06 Box Beam or Gird.- Sgl.e or spread
07 Frame
08 Orthotropic
09 Truss - Deck
10 Truss - Thru
11 Arch - Deck
12 Arch Thru
13 Suspension
14 Stayed Girder
15 Movable - Lift
16 Movable - Bascule
17 Movable - Swing
18 Tunnel
19 Culvert
00 Other

TABLE 4. Bridges Ranked in Descending Order by Total Deficiency Points

IDR	ID	TC	LCP	LP	HP	VP	DL	ADTO	KF	CRF	N2	DP
1	142	AA	39.23	4.17	15	0	99	4836	3.67	1.1	1	235.7608
2	140	AA	19.65	0	15	0	99	6500	4.76	1.1	1	181.4274
3	235	C	60	10	15	0	99	760	0.86	1.1	2	160.82
4	141	AA	19.02	0	15	0	99	4987	3.77	1.1	1	141.0809
5	101	AAA	0	0	15	0	99	10680	7.47	1	1	112.05
6	1	AAA	0	4.17	15	0	99	6400	4.7	1	1	90.099
7	2	AAA	0	4.17	15	0	99	6400	4.7	1	1	90.099
8	147	A	37.87	4.17	15	0	12	7500	1.34	1	1	76.4336
9	100	AAA	0	0	10	0	86	10951	6.75	1	1	67.5
10	248	C	60	10	15	0	15	412	0.36	1.1	2	67.32
11	228	C	60	10	15	0	10	301	0.31	1.2	2	63.24
12	18	AAA	0	0	15	0	71	7603	4.15	1	1	62.25
13	116	AAA	2.55	0	15	2.5	28	12168	3.03	1	1	60.7515
14	143	A	59.96	8.33	15	0	5	3542	0.73	0.9	1	54.72153
15	154	C	60	8.33	15	2.5	1	1550	0.49	1	1	42.0567
16	153	C	60	10	15	0	10	50	0.18	1.2	2	36.72
17	236	C	52.03	8.33	15	0	99	253	0.44	1.1	1	36.47424
18	4	AAA	0	4.17	15	0	39	3849	1.57	1.15	1	34.61143
19	5	AAA	0.42	4.17	15	0	39	4121	1.65	1	1	32.3235
20	3	AAA	0.55	4.17	15	0	39	4237	1.69	0.95	1	31.66046
21	184	C	60	10	5	2.5	5	50	0.17	1.2	2	31.62
22	239	C	40.02	8.33	15	0	99	253	0.44	1.1	1	30.6614
23	227	C	32.02	8.33	15	0	6	1264	0.5	1.1	1	30.4425
24	238	C	40.02	8.33	15	7.5	6	633	0.39	1.1	1	30.39465
25	37	AAA	5.29	1.67	5	0	40	6790	2.45	1	1	29.302
26	31	A	37.87	4.17	15	0	4	1382	0.5	1	1	28.52
27	245	C	60	8.33	15	0	99	127	0.31	1.1	1	28.41553
28	265	C	52.03	8.33	15	0	8	300	0.31	1.2	1	28.03392
29	197	C	56.03	8.33	15	0	5	350	0.32	1.1	1	27.93472
30	133	A	44.18	8.33	15	0	2	745	0.4	1	1	27.004
31	91	C	48.02	8.33	15	0	9	300	0.31	1.2	1	26.5422
32	128	A	34.72	8.33	15	0	99	264	0.45	1	1	26.1225
33	242	C	60	9.17	15	0	99	127	0.31	1	1	26.0927
34	139	AAA	0	0	15	0	26	7163	1.93	0.9	1	26.055
35	247	C	60	8.33	15	0	99	127	0.31	1	1	25.8323
36	263	C	52.03	8.33	15	0	9	400	0.34	1	1	25.6224
37	176	C	60	10	15	0	3	222	0.27	1.1	1	25.245
38	28	A	37.87	8.33	15	0	6	549	0.37	1.1	1	24.9084
39	145	A	31.56	4.17	15	0	5	1245	0.49	1	1	24.8577
40	246	C	56.03	8.33	15	0	99	127	0.31	1	1	24.6016
41	252	C	56.03	8.33	15	0	99	127	0.31	1	1	24.6016
42	237	C	60	8.33	15	0	4	253	0.29	1	1	24.1657
43	129	A	31.56	4.17	15	0	1	1324	0.47	1	1	23.8431
44	201	C	60	8.33	15	0	5	175	0.26	1.1	1	23.83238
45	98	A	44.18	10	15	2.5	2	300	0.3	1.1	1	23.6544
46	250	C	52.03	8.33	15	0	99	127	0.31	1	1	23.3616
47	137	A	37.87	4.17	15	0	7	483	0.36	1.1	1	22.58784
48	198	C	52.03	8.33	15	0	99	100	0.27	1.1	1	22.38192
49	115	A	34.72	4.17	15	0	1	868	0.41	1	1	22.0949
50	185	C	60	8.33	15	0	10	10	0.11	1.2	2	21.99912

Table 5. Bridge Ranking by Priority Factor

RPF	ID	TC	LCP	LCFR	LP	HP	VP	ADTO	DL	KF	CRF	N2	DP	CI	PF	SR	ST	CPADT
1	248	C	72.03	60	10	15	0	412	15	0.36	1.1	2	67.320	65	1.036	2	302	0.158
2	142	M	39.23	39.23	4.17	15	0	4836	99	3.67	1.1	1	235.761	246	0.958	25.3	101	0.051
3	140	M	19.65	19.65	0	15	0	6500	99	4.76	1.1	1	181.427	200	0.907	33.4	101	0.031
4	141	M	19.02	19.02	0	15	0	4987	99	3.77	1.1	1	141.081	200	0.705	30.3	101	0.040
5	250	C	52.03	52.03	8.33	15	0	127	99	0.31	1	1	23.362	50	0.467	2	302	0.394
6	196	C	72.03	60	10	15	0	222	3	0.27	1.1	1	25.245	56	0.451	18	310	0.252
7	239	C	40.02	40.02	8.33	15	0	253	99	0.44	1.1	1	30.661	70	0.438	3	302	0.277
8	242	C	60.03	60	9.17	15	0	127	99	0.31	1	1	26.093	65	0.401	7.4	302	0.512
9	130	MA	0	0	0	15	0	5119	4	0.82	0.95	1	11.685	30	0.389	48.8	104	0.006
10	245	C	60.03	60	8.33	15	0	127	99	0.31	1.1	1	28.416	75	0.379	3	302	0.591
11	247	C	60.03	60	8.33	15	0	127	99	0.31	1	1	25.832	71	0.364	8.5	302	0.559
12	200	C	60.03	60	8.33	15	0	125	4	0.23	1	1	19.166	53	0.362	18.9	302	0.424
13	197	C	56.03	56.03	8.33	15	0	350	5	0.32	1.1	1	27.935	100	0.279	18.1	310	0.286
14	249	C	40.02	40.02	8.33	15	0	127	99	0.31	1	1	19.638	72	0.273	3	302	0.567
15	198	C	52.03	52.03	8.33	15	0	100	99	0.27	1.1	1	22.382	85	0.263	3	310	0.850
16	147	A	37.87	37.87	4.17	15	0	7500	12	1.34	1	1	76.434	300	0.255	25.2	302	0.040
17	251	C	52.03	52.03	8.33	15	0	38	99	0.18	1	1	13.565	55	0.247	7.5	302	1.447
18	246	C	56.03	56.03	8.33	15	0	127	99	0.31	1	1	24.602	110	0.224	3	402	0.866
19	28	A	37.87	37.87	8.33	15	0	549	6	0.37	1.1	1	24.908	113	0.220	28.3	702	0.206
20	244	C	48.02	48.02	5	15	0	63	99	0.22	1.1	1	16.461	75	0.219	7.5	402	1.190
21	234	C	36.02	36.02	5	15	0	100	99	0.27	1.1	1	16.638	80	0.208	12.7	302	0.800
22	57	A	31.56	31.56	6.67	15	0	108	5	0.22	1	1	11.711	61	0.192	19.1	302	0.565
23	143	A	59.96	59.96	8.33	15	0	3542	5	0.73	0.9	1	54.722	300	0.182	24.8	104	0.085
24	210	C	32.02	32.02	4.17	0	0	1000	4	0.45	1	1	16.285	92	0.177	32.8	119	0.092
25	129	A	31.56	31.56	4.17	15	0	1324	1	0.47	1	1	23.843	140	0.170	12.8	302	0.106
26	232	C	24.01	24.01	5	15	0	100	99	0.27	1	1	11.883	70	0.170	32	302	0.700
27	240	C	60.03	60	9.17	15	0	63	99	0.22	1.1	1	20.369	125	0.163	7.9	302	1.984
28	255	C	60.03	60	8.33	15	0	100	5	0.22	1.1	1	20.166	127	0.159	16.9	302	1.270
29	230	C	60.03	60	10	15	0	13	99	0.12	1	1	10.200	68	0.150	19.2	302	5.231
30	202	C	24.01	24.01	4.17	5	0	300	4	0.3	1.2	1	11.945	81	0.147	17.1	101	0.270
31	225	C	52.03	52.03	8.33	15	0	100	11	0.22	1.1	1	18.237	125	0.146	24.7	702	1.250
32	231	C	72.03	60	10	15	0	13	99	0.12	1.1	1	11.220	80	0.140	13.8	302	6.154
33	233	C	44.02	44.02	5	15	0	20	99	0.14	1	1	8.963	65	0.138	31.4	302	3.250
34	191	C	72.03	60	10	15	0	100	1	0.21	1.1	1	19.635	144	0.136	17.8	402	1.440
35	195	C	60.03	60	8.33	15	0	75	2	0.2	1	1	16.666	133	0.125	17.8	302	1.773
36	214	C	60.03	60	8.33	10	0	50	7	0.17	1.1	1	14.648	117	0.125	24.3	302	2.340
37	212	C	32.02	32.02	4.17	15	0	40	99	0.19	1.1	1	10.699	86	0.124	4.4	302	2.150
38	208	C	32.02	32.02	8.33	5	0	400	6	0.34	1.2	1	18.503	152	0.122	9.3	101	0.380
39	241	C	60.03	60	9.17	15	0	38	99	0.18	1.2	1	18.181	150	0.121	11.7	702	3.947
40	177	C	0	0	0	15	0	75	4	0.2	1	2	6.000	50	0.120	17.2	302	0.667
41	35	A	37.87	37.87	4.17	15	0	522	10	0.38	1	1	21.675	192	0.113	4.5	302	0.368
42	152	C	40.02	40.02	8.33	15	0	300	1	0.3	1	1	19.005	169	0.112	31.7	302	0.563
43	206	C	12.01	12.01	4.17	10	0	1500	3	0.51	1	1	13.352	120	0.111	14.8	104	0.080
44	34	A	37.87	37.87	4.17	15	0	1382	4	0.5	1	1	28.520	260	0.110	36.9	100	0.188
45	235	C	72.03	60	10	15	0	760	99	0.86	1.1	2	160.820	1500	0.107	2	313	1.974
46	115	A	34.72	34.72	4.17	15	0	868	1	0.41	1	1	22.095	207	0.107	38	302	0.238
47	213	C	24.01	24.01	4.17	15	0	100	9	0.22	1.1	1	10.450	98	0.107	17.6	302	0.980
48	207	C	12.01	12.01	4.17	15	0	800	3	0.41	1	1	12.784	120	0.107	5.3	104	0.150
49	257	C	20.01	20.01	4.17	15	0	225	7	0.28	1	1	10.970	104	0.105	23.8	310	0.462
50	185	C	72.03	60	8.33	15	0	10	10	0.11	1.2	2	21.999	210	0.105	19.1	310	21.000

Table 6. Bridge Ranking by Net Benefit Equation

RANKING FACTOR RF=(DP*ADT/SUM(DP*ADT))-(CI/SUM CI)

IDCA	ID	DP	CI	ADTO	RF	TC
1	147	79.17	300000	7500	7.1255	A
2	140	82.5	290000	6500	6.4882	AA
3	142	87.087	246000	4836	5.0291	AA
4	141	82.5	200000	4987	4.9431	AA
5	143	74.997	300000	3542	3.0638	A
6	39	29.9	615000	6790	2.0533	AAA
7	64	9.5	200000	15394	1.6607	A
8	40	27.1	590000	5200	1.3033	AAA
9	19	17.34	345000	5640	0.9527	AAA
10	139	13.5	380000	7163	0.9129	AAA
11	248	187	65000	412	0.9051	C
12	18	15	682000	7603	0.9019	AAA
13	135	38.55	325000	2391	0.8980	A
14	130	14.25	30000	5119	0.8805	AAA
15	34	59.72	260000	1382	0.8273	A
16	154	57.15	512000	1550	0.7138	C
17	129	47.07	140000	1324	0.6668	A
18	119	16.0265	370000	4667	0.6493	AAA
19	235	187	1500000	760	0.6381	C
20	4	22.0455	592000	3849	0.6078	AAA
21	2	19.17	1250000	6400	0.5844	AAA
22	5	19.87	603000	4121	0.5629	AAA
23	113	14.481	257000	4042	0.5324	AAA
24	209	39.853	635000	2000	0.5120	C
25	10	28.15	337000	2060	0.4659	A
26	9	27.85	336000	2060	0.4590	A
27	126	41.216	475000	1577	0.4495	A
28	24	44.495	230000	1128	0.4493	A
29	3	19.095	782000	4237	0.4170	AAA
30	227	66.033	827000	1264	0.4150	C
31	206	26.56	120000	1500	0.4034	C
32	48	16.731	248000	2661	0.3657	AAA
33	210	34.18	92000	1000	0.3543	C
34	49	16.731	270000	2661	0.3493	AAA
35	115	45.78	207000	868	0.3371	A
36	28	57.915	113000	549	0.3091	A
37	87	15	475000	3500	0.2948	AAA
38	42	13.869	305000	3018	0.2901	AAA
39	131	42.332	240000	873	0.2781	A
40	149	68.772	252000	500	0.2373	C
41	239	91.663	70000	253	0.2347	C
42	41	21.375	425000	2041	0.2224	AA
43	197	65.703	100000	350	0.2099	C
44	109	23.004	270000	1410	0.1997	A
45	207	28.77	120000	800	0.1952	C
46	70	32.48	795000	1957	0.1926	A
47	35	51.18	192000	522	0.1872	A
48	138	9.1485	250000	3180	0.1733	AAA
49	196	69.421	56000	222	0.1489	C
50	71	37.9	280000	717	0.1271	A

TABLE 7. Comparison of Costs and Benefits for the 10 Top-Ranked Bridges Using Seven Different Ranking Equations

	Eq.7	Eq. 12	Eq.13	Eq.14	Eq.15	Eq.16	Eq.17
Σ CI ($ x 10^6)	2.012	3.376	2.491	2.114	1.778	1.996	1.981
DP removed	657	503	506	623	612	630	637
ADTO 36,261		31,250	67,552	57,374	38,310	34,897	36,607
ΣDPxADTO (x 10^6)	20.53	33.79	32.51.	23.78	21.41	23.06	23.09
CI/ADTO ($)	64.38	49.97	43.41	55.44	50.93	54.52	54.63
CI/DP ($)	3,062	6,711	4,395	3,389	2,911	3,168	3,109
CI/DPxADTO ($ x 10^2)	9.80	9.93	7.66	8.88	8.32	8.65	8.50

Notes. 1. All rankings were conducted on "A", "AA", and "AAA" bridges of the original 267 bridge data set.

2. Eq. 7 - RF = DP/CI

Eq. 12 - RF = (DP x ADTO/Σ DP x ADTO) - CI/Σ CI)

Eq. 13 - RF = (DP x ADTO/CI)

Eq. 14 - RF = (DP^2 x ADTO/CI)

Eq. 15 - RF = (DP x $ADTO^{0.5}$/CI)

Eq. 16 - RF = (DP^2 x $ADTO^{0.5}$/CI)

TABLE 8. Bridges Ranked in Order by Annual Net Benefits

RANK	ID	TC	ADT	DL	PT	POST	LCP	VP	WP	CI	NB
1	246	AA	4836	99	7.1	A	49.81	0.00	15.00	246000	273656870
2	244	AA	6500	99	4	A	39.72	0.00	15.00	200000	166501145
3	245	AA	4987	99	7.1	A	25.87	0.00	15.00	200000	147407387
4	250	A	3924	60	4.2	P	70.00	0.00	15.00	719000	102264846
5	19	AAA	2119	7C	9.7	P	42.30	0.00	15.00	373000	80556583
6	247	AAA	4038	99	7.1	P	14.68	0.00	15.00	578000	68305223
7	18	AAA	2038	70	9.7	P	37.06	0.00	15.00	317000	67958280
8	243	AAA	8272	99	4	P	9.59	0.00	15.00	778000	48481232
9	140	AAA	3240	30	6.7	P	37.06	0.00	15.00	384000	36259509
10	232	A	3259	64	4.2	P	25.77	0.00	0.00	85000	36251117
11	231	A	3259	64	4.2	P	25.77	0.00	0.00	86000	36251000
12	306	C	760	99	4	P	70.00	0.00	15.00	1500000	33932359
13	251	A	1524	99	4	P	25.77	0.00	15.00	85000	23200530
14	225	A	400	99	4	P	70.00	0.00	15.00	501000	16261033
15	34	AAA	6790	40	5.9	A	6.17	0.00	5.00	615000	15112000
16	8	AA	720	39	8.9	P	33.67	0.00	15.00	336000	12481205
17	9	AA	720	39	8.9	P	33.67	0.00	15.00	336000	12481205
18	10	AA	720	39	8.9	P	33.67	0.00	15.00	449000	12467932
19	258	A	7500	12	1.5	P	49.71	0.00	15.00	300000	12225762
20	307	C	253	99	4	P	70.00	0.00	15.00	405000	11306985
21	21	AAA	7603	71	6.3	A	1.78	0.00	15.00	682000	11244648
22	141	AAA	2430	11	6.7	P	37.06	0.00	15.00	279000	10456559
23	213	AA	2301	14	4.2	P	36.69	0.00	10.00	320000	8876906
24	124	AA	5100	13	4.8	P	13.55	0.00	15.00	1885000	8545593
25	188	AAA	4042	26	4.2	P	12.25	0.00	15.00	257000	8268277
26	248	A	3542	5	4.2	P	70.00	0.00	15.00	300000	7853611
27	319	C	500	35	4	P	70.00	0.00	15.00	90000	7307679
28	321	C	150	99	4	P	70.00	0.00	15.00	215000	7012694
29	206	A	264	99	4	P	45.56	0.00	15.00	550000	6976862
30	192	AAA	12168	28	2.5	A	2.98	0.00	15.00	8000000	6760936
31	241	AA	1376	99	4.2	P	7.20	0.00	15.00	930000	6355418
32	293	C	9600	5	3	P	14.01	0.00	15.00	300000	6063194
33	287	C	100	99	5.4	A	70.00	0.00	15.00	85000	6036124
34	106	AAA	8602	1	4.8	P	70.00	15.00	15.00	30400000	5968972
35	6	AAA	2728	46	9.7	P	2.81	0.00	15.00	409000	5847452
36	15	AAA	2070	79	9.7	A	2.30	0.00	15.00	846000	5596897
37	53	AAA	2661	18	10.2	P	7.73	0.00	10.00	248000	5454780
38	54	AAA	2661	18	10.2	P	7.73	0.00	10.00	270000	5452196
39	184	A	189	99	4	P	49.71	0.00	15.00	373000	5449869
40	14	A	1674	5	8.9	P	45.56	0.00	15.00	634000	5431052
41	20	AAA	1921	50	9.7	P	3.69	0.00	15.00	560000	5299665
42	323	C	127	99	4	P	70.00	0.00	15.00	50000	5175689
43	186	AAA	813	33	4.2	P	30.59	0.00	15.00	2802000	4969994
44	315	C	127	99	4	A	66.77	0.00	15.00	71000	4935813
45	334	C	2446	5	4.8	P	42.95	0.00	15.00	380000	4888947
46	109	A	10500	2	4.8	P	0.00	15.00	15.00	7150000	4816931
47	197	AAA	1132	30	7.1	A	14.33	0.00	15.00	525000	4812421
48	125	AA	2900	9	6.7	A	13.05	0.00	15.00	305000	4676860
49	38	AA	2260	2	8.9	P	70.00	0.00	15.00	260000	4580486
50	322	C	100	99	4	P	70.00	0.00	15.00	215000	4462713